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Loading the LES-9 Wideband
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B.F. McGuffin

21 June 1990

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS



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LOADING THE LES-9 WIDEBAND UHF TRANSPONDER

B.F. McGUFFIN
Group 64



TECHNICAL REPORT 882

21 JUNE 1990

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ABSTRACT

This report describes results of a loading study performed for the LES-9 wide-band UHF transponder. The study goal was to improve service quality, and increase satellite utilization by scheduling more concurrent users.

Power-sharing models for LES-9 are developed using the time-domain model for nonlinear transponders. All nonsignal transponder output power is treated as noise, with power spectrum uniformly distributed across the transponder bandwidth.

Compatible groups of users are found for LES-9, supporting common user terminal configurations. Based on the results of this study, it is recommended that all users be allowed to increase uplink power.

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1. INTRODUCTION AND SUMMARY

This report describes results of a loading study performed for the LES-9 wideband UHF transponder. This transponder hardlimits the input signal, allowing the transponder amplifier to operate in saturation, thus maximizing power efficiency. When multiple input signals share the hardlimited channel, transponder output power divides unevenly among the signals, with stronger signals tending to suppress weaker ones. Intermodulation products resulting from the nonlinearity introduce additional interference on the satellite downlink. Currently, power suppression and intermodulation are controlled by limiting the total number of simultaneous users to a maximum of five, and limiting maximum user EIRP to 19 dBW for 16-kbps users and 16 dBW for lower data-rate users. This study was prompted by increasing demand for LES-9 wideband UHF transponder service, and continuing problems with quality of service when several users share the transponder. Study goals were to develop a model of the shared nonlinear transponder that would indicate limitations on LES-9 service, hopefully providing improved service quality and increased throughput by allowing larger groups of simultaneous users (user sets).

In this report, power-sharing models are developed for the hardlimiting transponder, using what is known as the time-domain model [1,2] to compute the transponder SNR suppression ratio for each member of a user set. Compatible user sets are assembled by comparing available CNR at the receiving ground terminals with minimum requirements for acceptable service quality for each user set member. The user set specifies both how many users may be supported, and maximum EIRP for each user.

The time-domain model provides actual expressions for the instantaneous output signal (or noise or intermodulation-product) envelopes as a function of input signals and noise. This method differs from previous results [3,4], sometimes referred to as frequency-domain results, which produce the transponder-output autocorrelation. Terms of the derived autocorrelation function are then assumed to arise from different sources [5] - signal feedthrough, noise feedthrough, and intermodulation products - allowing the power of each output component to be calculated. The time-domain model has several advantages over frequency-domain models: it can model amplitude or phase modulated signals, it can be used with arbitrary nonlinearities, and it fully describes baseband signal distortion which cannot always be calculated from frequency-domain results [2]. It also appears that, where either approach is applicable (PM or FM signals through a bandpass hardlimiter), the time-domain model requires less computer time. Similar results to those used here for calculating hardlimiting transponder output power were reported recently [6].

When using transponder output-signal power to find SNR suppression, intermodulation products are not modeled explicitly. Instead, all nonsignal transponder output power is treated as noise, with uniform Power Spectrum Density (PSD) across the transponder bandwidth.

Based on this procedure, it is recommended that uplink signal EIRPs be raised for all users: to 27.9 dBW for 16-kbps users, and 23 dBW for lower data-rate users. Compatible user sets with increased uplink EIRP provide 3-dB power margins for up to four 16-kbps users, or ten lower data-rate users, or some combination of users at both power levels.

Section 2 summarizes characteristics of the LES-9 satellite and its wideband UHF transponder. The AN/URC-110 ground terminal, the most common terminal supported by LES-9, is described in Section 3. Section 4 contains uplink and downlink power budgets based on LES-9 and AN/URC-110 characteristics. In Section 5, we describe the loading model used to determine individual user performance in a given user set, with SNR-suppression factors produced by the time-domain model.

Section 6 applies the loading model to user sets based on currently specified power restrictions. It is shown that, as expected, current service quality is poor. With five (the currently specified maximum number) or more users present, only 2.4-kbps users attain 3-dB overall link margins. A single 16-kbps signal with exclusive use of the transponder will have a 1-dB link margin. It is demonstrated that current service is limited by uplink power restrictions.

In Section 7, we discuss increasing uplink power levels to improve service quality and LES-9 throughput. If 16-kbps signals are allowed to transmit with an EIRP of 27.9 dBW (maximum AN/URC-110 EIRP) and lower-rate signals transmit with 23-dBW EIRP, then user sets consisting of as many as four 16-kbps signals may share the transponder with 3-dB link margin for each user. Larger user sets are possible when some or all signals in the set have data rates below 16 kbps.

Section 8 summarizes the report and recommends additional work in this area.

Appendix A contains tables of ground-terminal received CNR for different users and user sets, based on currently specified uplink power levels. Tables and contour plots of ground-terminal CNR for different users and user sets, based on recommended uplink power levels, are contained in Appendix B. Appendix C outlines the derivation of SNR-suppression ratios, using the time-domain model for a hardlimiting transponder. Appendix D defines acronyms and abbreviations used in this report.

2. TRANSPONDER CHARACTERISTICS

The LES-9 wideband UHF transponder is a frequency-translation hardlimiting transponder, serving a variety of users in the UHF/UHF frequency band. Transponder characteristics [7] are listed in Table 2-1.

TABLE 2-1.

LES-9 Wideband UHF Transponder Characteristics

Received Center Frequency	303.4 MHz
Transmitted Center Frequency	249.6 MHz
Bandwidth (3 dB)	550 kHz
Antenna Gain (@ 250 MHz)	8.0 to 10.0 dBI
Antenna Gain (@ 300 MHz)	8.0 to 9.5 dBI
Antenna Polarization	Right-hand circular polarization
System Noise Temperature	831 K
One-Sided System Noise PSD	-199.4 dBW/Hz
Transmitter Power	15 dBW

The LES-9 satellite is in an inclined, circular, geosynchronous orbit. In 1989, LES-9 was located at 105° W longitude, oscillating daily between 21° N latitude and 21° S latitude. Antenna gain seen by a geographically fixed user will vary through the range of Table 2-1 with a period of one sidereal day, as relative satellite orientation varies during each orbit.

Transmission path loss for a fixed user also will vary over one sidereal day, as changing sub-satellite latitude alters the distance between the terminal and satellite. The range of path-loss values is listed in Table 2-2 [7].

TABLE 2-2.

LES-9 UHF Path Loss

Uplink Path Loss (dB)	Minimum:	173.2
	Maximum:	174.5
	Average:	173.9
Downlink Path Loss (dB)	Minimum:	171.7
	Maximum:	173.0
	Average:	172.4

3. TERMINAL CHARACTERISTICS

The most common terminal supported by LES-9 is the AN/URC-110. Terminal characteristics are listed in Table 3-1 [8].

TABLE 3-1.
AN/URC-110 Ground-Terminal Characteristics

Transmit	Maximum power	13.5 dBW
	Antenna gain	14.4 dBi
	Maximum EIRP	27.9 dBW
Receive	Antenna gain	14.4 dBi
	G_r/T_{sys}	-14.2 dB K ⁻¹
	One-sided system noise PSD	-200.0 dBW/Hz

When used with LES-9, the AN/URC-110 terminal may employ BPSK or FSK modulation, with data rates ranging from 2.4 to 16 kbps. Common terminal configurations and minimum performance requirements are listed in Table 3-2 [8]. Specified EIRPs in Table 3-2 are maximum allowed values specified to control power-sharing in the LES-9 nonlinear transponder, and do not reflect terminal capability.

TABLE 3-2.
AN/URC-110 Configurations and Performance Requirements

Modem	Data Rate (kbps)	Modulation	Specified EIRP (dBW)	Required CNR (dB Hz)
KY-57	16	FSK	19	51.2
ANDVT	4.8	BPSK	16	46
ANDVT	2.4	BPSK	16	43

In this report, the term "user" will refer to one transmitting and one receiving terminal linked together via the LES-9 wideband UHF transponder, and employing one of the three configurations listed in Table 3-2.

4. LINK BUDGETS

Because 2.4- and 4.8-kbps signals are allowed the same uplink EIRP, their received CNRs will be the same in an otherwise identical user set. Conversely, a 2.4- or a 4.8-kbps signal will affect co-user signal suppression identically. When only signal power level is relevant, these two formats will be grouped together as low-power (LP) signals, and 16-kbps signals will be referred to as high-power (HP) signals.

Table 4-1 contains power budgets for LP and HP uplinks. The downlink budget for total received power (all signals plus downlink noise) is given in Table 4-2. Both tables assume average path loss and 9-dBI transponder antenna gain for transmit and receive.

TABLE 4-1.

Uplink Power Budgets

	HP Signal	LP Signal
Terminal EIRP (dBW)	19.0	16.0
Path Loss (dB)	173.9	173.9
Satellite Receive Antenna Gain (dBI)	9.0	9.0
Transponder Received Signal Power (P_t) (dBW)	-145.9	-148.9
One-Sided System Noise PSD (dBW/Hz)	-199.4	-199.4
Transponder Bandwidth (kHz)	550	550
System Noise Power (dBW)	-142.0	-142.0
Satellite SNR_{in} (dB)	-3.9	-6.9

TABLE 4-2.

Downlink Power Budget

Satellite Transmitter Power	15.0 dBW
Satellite Transmit Antenna Gain	9.0 dBI
Path Loss	172.4
Terminal Receive Antenna Gain	14.4 dBI
Terminal Total Received Power (P_r)	-134.0 dBW

5. LOADING MODEL

In order to identify compatible user sets, received CNR for each user is computed in the presence of the specified interfering co-users. If each user in a set receives its desired signal with some predetermined margin above the required CNR of Table 3-2, then the user set is considered compatible.

In computing the received CNR for a particular user, it is assumed that co-users are spaced sufficiently far apart in frequency to ignore linear interchannel interference. Transponder throughput noise, nonlinear signal distortion, and intermodulation are lumped together into a single interfering downlink noise signal, which is assumed to have a uniform PSD across the transponder bandwidth.

Total received power at the user's terminal is made up of $L + 1$ components, for a user set with L members: L transponded signals, and downlink noise. If total received power is P_r , and the transponded signal from the l^{th} user has power $S_r(l)$, then downlink noise power is $N_r = P_r - \sum_{l=1}^L S_r(l)$. Note that N_r is not defined as a noise power density, but is the actual noise power. Received power due to the desired signal is equal to P_r times the ratio of desired signal power to the summed total of power in all $L + 1$ components. If the numerator and denominator of this ratio are both normalized by N_r , the result is an expression for received power in the desired signal as a function of total received power and transponder output SNRs:

$$S_r(i) = P_r \frac{S_r(i)/N_r}{1 + \sum_{l=1}^L S_r(l)/N_r}. \quad (5.1)$$

Proceeding as above for the downlink noise component:

$$N_r = P_r \frac{1}{1 + \sum_{l=1}^L S_r(l)/N_r}. \quad (5.2)$$

In order to know the received signal and noise powers, it is necessary to know total received power and transponder SNRs.

Transponder output SNR for each signal is related to its transponder input SNR by the SNR-suppression ratio:

$$\alpha_i = \frac{S_r(i)/N_r}{S_t(i)/N_t} \quad (5.3)$$

where $S_t(i)$ is signal i power received at the transponder, and N_t is transponder front-end noise power. The SNR-suppression ratio for each user is a function of all input signal powers, transponder front-end noise power, and the transponder nonlinearity. Suppression ratios are easily calculated for the case of a hardlimiting transponder using the time-domain model for bandpass limiters, as described in Appendix C.

The desired CNR at the user terminal is found by dividing received signal power by the total noise power density, which is the sum of receiver one-sided noise PSD, N_d , and the ratio of N_r to the transponder bandwidth B_t :

$$\text{CNR}_i = \frac{S_r(i)}{N_d + N_r/B_t} \quad (5.4)$$

All the equations presented in this section are written in the linear domain. When calculating actual CNR values, it will be convenient to work with quantities in decibels, converting to the linear domain only when one or more quantities must be summed. The equations given here must be modified as appropriate. The following example demonstrates how CNR can be calculated.

Example:

Consider a user set with three members: two HP users and one LP user. From Table 4-1, received SNRs at the transponder are -3.85 and -6.85 dB, respectively. Using Equation (C.8) of Appendix C, we find that SNR suppression is -1.68 dB for the LP user and -1.41 dB for each HP user. Thus, output SNRs are -5.26 dB = 0.298 for HP and -8.53 dB = 0.140 for LP users. From Table 4-2, total received power is -134.0 dBW. Using these quantities, received signal power for an HP user can be found using Equation (5.1) as:

$$S_r(\text{HP}) = P_r \text{ dBW} + \frac{S_r(\text{HP})}{N_r} \text{ dB} - 10 \log \left[1 + 2 \frac{S_r(\text{HP})}{N_r} + \frac{S_r(\text{LP})}{N_r} \right] \quad (5.5)$$

$$= -134 \text{ dBW} - 5.26 \text{ dB} - 10 \log[1 + 2(0.298) + 0.140] \quad (5.6)$$

$$= -141.61 \text{ dBW}. \quad (5.7)$$

Proceeding similarly for the LP user produces $S_r(\text{LP}) = -144.88 \text{ dBW}$. Received noise power is found using Equation (5.2):

$$N_r = P_r \text{ dBW} - 10 \log \left[1 + 2 \frac{S_r(\text{HP})}{N_r} + \frac{S_r(\text{LP})}{N_r} \right] \quad (5.8)$$

$$= -134 \text{ dBW} - 10 \log[1 + 2(0.298) + 0.140] \quad (5.9)$$

$$= -136.35 \text{ dBW} \quad (5.10)$$

which is equivalent to $2.32 \times 10^{-14} \text{ W}$. Received noise PSD is $N_r/B_t = 4.21 \times 10^{-20} \text{ W/Hz}$. Terminal system noise PSD is listed in Table 3-1 as $N_d = -200 \text{ dBW/Hz}$, which is equivalent to 10^{-20} W/Hz . Using Equation (5.4), the CNR for an HP user is

$$\text{CNR}(\text{HP}) = S_r(\text{HP}) \text{ dBW} - 10 \log(N_d + N_r/B_t) \quad (5.11)$$

$$= -141.61 \text{ dBW} - 10 \log(10^{-20} + 4.21 \times 10^{-20}) \quad (5.12)$$

$$= 51.22 \text{ dB Hz}. \quad (5.13)$$

Proceeding similarly for the LP signal, $\text{CNR}(\text{LP}) = 47.95 \text{ dB Hz}$.

Equations (5.1) through (5.4) can be combined to write the i^{th} user's received CNR as:

$$\text{CNR}_i = \frac{P_r \frac{\alpha_i S_i(i)/N_t}{1 + \sum_{l=1}^L \alpha_l S_i(l)/N_t}}{N_d + \frac{P_r}{B_t} \frac{1}{1 + \sum_{l=1}^L \alpha_l S_i(l)/N_t}} \quad (5.14)$$

Tables 2-1 to 3-2 and Equation (5.14) are sufficient to determine if a user set is compatible, based on the data rate and path loss specified for each user-set member.

6. RESULTS

Possible user sets are specified by the number of LP and HP users in each set. We examined 120 different user sets for compatibility, with zero to ten LP users and zero to ten HP users in a set. Tables A-1 and A-2 of Appendix A list the terminal CNR with each user set, for an LP and an HP user, respectively.

Figures 6-1 and 6-2 are contour plots of the data in Appendix A. The lower left-hand corner of each figure represents the case of a single LP or HP user, respectively, with no co-users. Each step to the right adds an additional LP user to the user set, and each step up adds an additional HP user. Note that contour lines are nearly linear in the number of LP and HP users. Careful examination will reveal that contour lines are actually curved, particularly in the lower left-hand corner. It will be seen below that increasing transponder input SNR makes the contours noticeably curved for larger values of received CNR.

Looking at Tables A-1 and A-2, it is clear that CNR is relatively insensitive to the number of co-users. For small user sets, LP CNR is reduced by less than 1/3 (2/3) dB for each additional LP (HP) co-user. HP CNR is reduced by less than 1/2 (3/4) dB for each additional LP (HP) user. Degradation caused by each additional user declines as the user-set size grows, reaching approximately 0.6 times the initial drop (in decibels) when the tenth user is added.

Link performance is insensitive to the user-set size because the system is uplink-power limited. For instance, in the example of Section 5 received downlink noise PSD exceeded terminal system noise PSD by 6.2 dB. To further illustrate this point, Table 6-1 lists LP signal power (user 1), and the one-sided noise PSD of transponded satellite front-end noise at the downlink terminal for three user sets, with minimum uplink and downlink path loss. In every case, downlink noise density exceeds the AN/URC-110 receiver noise density by at least 4.7 dB. As the number of co-users (or co-user power) increases, desired-signal power loss is partially offset by suppression of transponder throughput noise, which dominates in the receiver.

TABLE 6-1.

Received LP-User Power and Transponder Throughput Noise Power Spectrum Density

Number of LP Users	Number of HP Users	$S_r(1)$ (dBW)	N_r/B_t (dBW/Hz)
1	0	-141.1	-192.3
10	0	-145.8	-194.1
1	9	-148.0	-195.3

Figure 6-3 shows the sensitivity of link performance to variations in uplink and downlink path loss. Each curve represents the received CNR for an LP user sharing the transponder with up to nine other LP users, and no HP users. Co-users experience average uplink path loss, while downlink and desired-user uplink path loss varies over the values of Table 2-2. This figure indicates that as

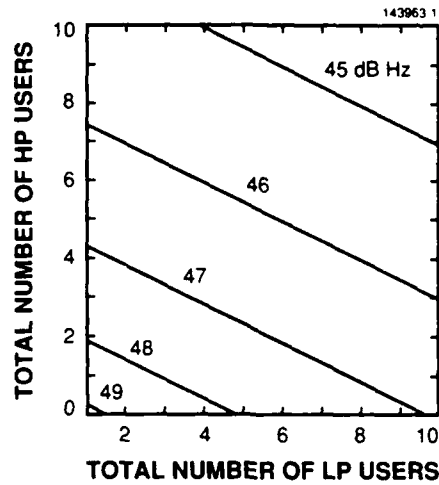


Figure 6-1. CNR contours for an LP user with other LP and HP users present; LP EIRP = 16 dBW, HP EIRP = 19 dBW.

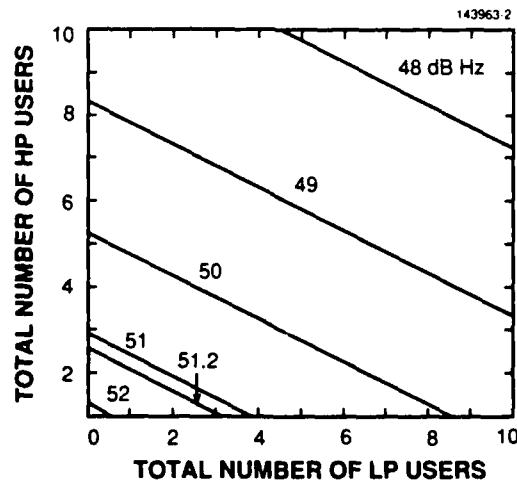


Figure 6-2. CNR contours for an HP user with other LP and HP users present; LP EIRP = 16 dBW, HP EIRP = 19 dBW.

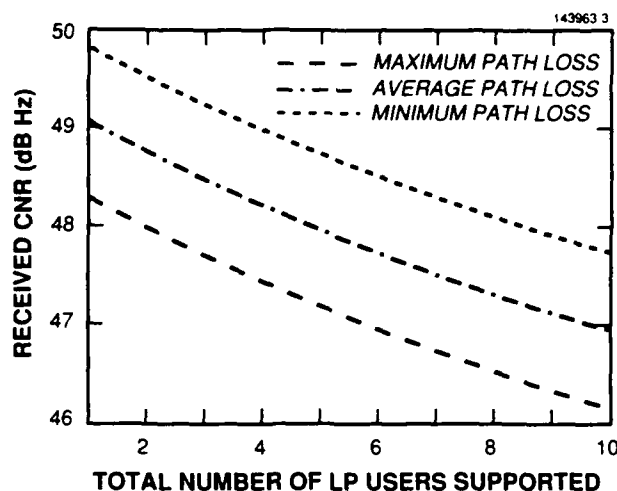


Figure 6-3. LP user sensitivity to path-loss variation, with other LP users; LP EIRP = 16 dBW.

path length varies, expected CNR values will differ from those of Tables A-1 and A-2 by slightly less than ± 1 dB. Other user sets produce similar results.

Tables A-1 and A-2 can be used to assemble compatible user sets, listed in Tables 6-2 through 6-5 for link margins ranging from 0 to 3 dB. Each column in the tables represents a compatible user set, listing the maximum number of users at each data rate that may be in the set. When user-set size is limited by HP-user CNR requirements, only the total number of LP users is listed. In this case, any combination of 4.8- and 2.4-kbps users whose total number does not exceed the given limit will be compatible with the HP users present. When user-set size is limited by LP-user performance, the allowable number of users is listed separately for each data rate, unless the total number of LP users happens to be invariant. For example, Set 2 of Table 6-3 may include up to nine LP users in any combination of 2.4- and 4.8-kbps users, while Set 3 of the same table may include up to ten 2.4-kbps users but no 4.8-kbps users. In this example, with ten LP users present, power suppression in the transponder prevents 4.8-kbps signals from maintaining the required power margin. Obviously, a user set made up of nine or fewer 2.4-kbps users may be arbitrarily considered to be a subset of either Set 2 or Set 3.

For users at the currently specified maximum uplink power levels, LES-9 can support as many as ten 2.4-kbps channels with greater than 3-dB link margin. However, system performance is not sufficient to support more than one 4.8-kbps channel with 3-dB link margin, and a single 16-kbps channel with exclusive use of the transponder will have approximately 1 dB of margin. Clearly, system performance at current power levels is not sufficient to allow increased transponder throughput, unless all channels with data rate above 2.4 kbps are excluded.

TABLE 6-2.

Compatible User Sets with 0-dB Link Margin

Data Rate (kbps)	Number of Users		
	Set 1	Set 2	Set 3
16	2	1	0
4.8	1	3	10
2.4	Total	Total	Total

TABLE 6-3.

Compatible User Sets with 1-dB Link Margin

Data Rate (kbps)	Number of Users		
	Set 1	Set 2	Set 3
16	1	0	0
4.8	0	9	0
2.4	0	Total	10

TABLE 6-4.

Compatible User Sets with 2-dB Link Margin

Data Rate (kbps)	Number of Users	
	Set 1	Set 2
16	0	0
4.8	4	0
2.4	total	10

TABLE 6-5.

Compatible User Sets with 3-dB Link Margin

Data Rate (kbps)	Number of Users	
	Set 1	Set 2
16	0	0
4.8	1	0
2.4	0	10

7. RECOMMENDATIONS

Tables 6-2 through 6-5 demonstrate that system performance is not adequate to support the current practice of scheduling up to five users in a set, unless all five are 2.4-kbps users. Discussions with the LES-9 operations center confirm that there has been a problem with link quality.

As demonstrated in Section 6, LES-9 service quality is limited by uplink SNR. Service quality can be improved by allowing all users to increase their EIRP. The maximum EIRP available from an AN/URC-110 terminal is 27.9 dBW [8], well above currently specified values. If some users are power-limited, it may be possible to schedule their services during specific time slots set aside for that purpose.

Selection of suitable HP- and LP-user power levels can proceed in two steps. First, the HP EIRP level is chosen to maximize HP throughput. Figure 7-1 plots the number of HP users that can be supported simultaneously, with no LP users present, as a function of HP EIRP. The figure assumes that each user's received CNR must be 3 dB above the value of Table 3-2 for good-quality service. The number of compatible HP users jumps to four at $\text{EIRP} = 27.5 \text{ dBW}$, which suggests that HP terminals should operate at full power, with $\text{EIRP} = 27.9 \text{ dBW}$.

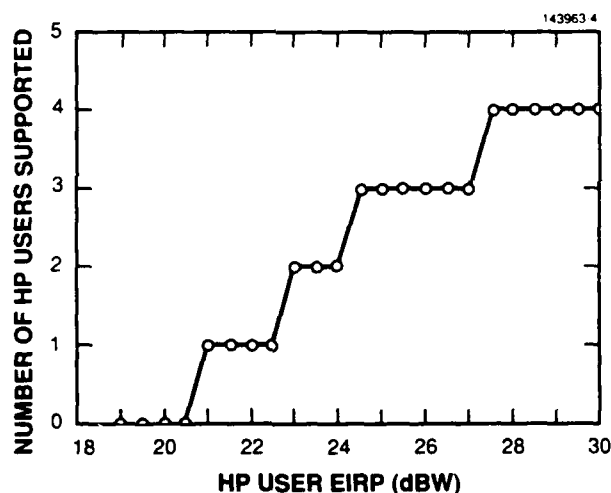


Figure 7-1. Transponder HP-signal throughput (3-dB margin).

The second step involves choosing LP-user EIRP to maximize transponder throughput when HP and LP users share the transponder, and HP EIRP is fixed at 27.9 dBW. Each user set is initially specified by the number of HP users supported. LP-user EIRP is chosen to maximize the number of LP users supported within a set, while maintaining minimum HP service quality with 3-dB margins. The resulting LP-user EIRP value is 23.0 dBW.

Appendix B contains tables and contour plots of received CNRs for the chosen EIRP values. Compatible user sets with 3-dB link margins are listed in Table 7-1.

TABLE 7-1.
Recommended User Sets with 3-dB Link Margin

Data Rate (kbps)	Number of Users					
	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6
16	4	3	2	1	1	0
4.8	0	3	6	9	0	10
2.4	0	Total	Total	Total	10	Total

8. CONCLUSIONS

The purpose of this study was to develop a model of the LES-9 wideband UHF transponder that could be used to determine maximum achievable transponder throughput while maintaining quality of service. This model was developed based on the time-domain model for memoryless nonlinearities, using a Bessel function expansion of the bandpass limiter single-tone envelope transfer function. Only the power-sharing problem was considered here. If desired, it is straightforward to use this model for finding the envelopes of intermodulation products, although computation time may be prohibitive.

Using the model developed, compatible user sets were identified for the LES-9 wideband UHF transponder to be used in conjunction with the AN/URC-110 ground terminal. With currently specified terminal EIRP constraints, compatible user sets were smaller than the current maximum user-set size for all but the lowest data-rate users. This result is consistent with reports of poor service quality by LES-9 users. However, it was noted that channel performance was limited by the uplink SNR. If all users increase ground terminal EIRP, system performance will improve and larger user sets can be scheduled.

Recommended EIRP values are the AN/URC-110 maximum value of 27.9 dBW for 16-kbps users, and 23.0 dBW for lower data-rate users. This plan will allow up to four 16-kbps users to be scheduled for LES-9 support, with a 3-dB power margin on each channel. With fewer 16-kbps users present, additional lower data-rate users may be scheduled, up to ten at one time.

Throughput can be further improved by continued refinement of the system or model. Possible improvements include allowing different maximum EIRP values for each data rate below 16 kbps, or assigning user center frequencies to minimize interference by intermodulation products.

It is also recommended that an experiment be performed using the LES-9 satellite, to verify analytical results used here for SNR suppression and CNR.

APPENDIX A

LINK PERFORMANCE AT CURRENT POWER LEVELS

This appendix contains tables of received HP- or LP-user CNR, for different user sets. Each user transmits with the EIRP value listed in Table 3-2, and experiences the average uplink and downlink path losses of Table 2-2.

Table A-1 lists received CNR for an LP user. User sets in this table consist of one to ten LP users (including the desired user), and zero to ten HP users. Table A-2 lists received CNR for an HP user; here, user sets contain zero to ten LP users, and one to ten HP users (including the desired user).

The line drawn through the body of each table separates user sets that meet the CNR requirements of Table 3-2 from those that do not, for 4.8-kbps users in Table A-1, and for 16-kbps users in Table A-2. All user sets shown meet 2.4-kbps user CNR requirements.

TABLE A-1.
LP-User CNR (dB Hz) for Different User Sets

Number of HP Users	Number of LP Users										
	0	1	2	3	4	5	6	7	8	9	10
0	NA	49.06	48.75	48.47	48.21	47.97	47.74	47.52	47.32	47.13	46.94
1	NA	48.44	48.19	47.95	47.73	47.52	47.31	47.12	46.94	46.76	46.60
2	NA	47.94	47.72	47.51	47.31	47.12	46.94	46.76	46.59	46.43	46.28
3	NA	47.51	47.31	47.12	46.93	46.76	46.59	46.43	46.28	46.13	45.98
4	NA	47.11	46.93	46.76	46.59	46.43	46.28	46.13	45.98	45.84	45.71
5	NA	46.76	46.59	46.43	46.27	46.13	45.98	45.84	45.71	45.58	45.45
6	NA	46.43	46.27	46.13	45.98	45.84	45.71	45.58	45.45	45.33	45.21
7	NA	46.12	45.98	45.84	45.71	45.58	45.45	45.33	45.21	45.09	44.98
8	NA	45.84	45.71	45.58	45.45	45.33	45.21	45.09	44.98	44.87	44.76
9	NA	45.58	45.45	45.33	45.21	45.09	44.98	44.87	44.76	44.66	44.55
10	NA	45.33	45.21	45.09	44.98	44.87	44.76	44.66	44.55	44.45	44.36

TABLE A-2.
HP-User CNR (dB Hz) for Different User Sets

Number of HP Users	Number of LP Users										
	0	1	2	3	4	5	6	7	8	9	10
0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1	52.22	51.85	51.53	51.24	50.98	50.74	50.52	50.31	50.11	49.92	49.74
2	51.49	51.22	50.97	50.73	50.51	50.30	50.11	49.92	49.74	49.57	49.41
3	50.96	50.72	50.50	50.30	50.10	49.91	49.74	49.57	49.40	49.25	49.10
4	50.50	50.29	50.10	49.91	49.73	49.57	49.40	49.25	49.10	48.95	48.81
5	50.09	49.91	49.73	49.56	49.40	49.25	49.10	48.95	48.81	48.68	48.54
6	49.73	49.56	49.40	49.24	49.09	48.95	48.81	48.67	48.54	48.42	48.29
7	49.40	49.24	49.09	48.95	48.81	48.67	48.54	48.42	48.29	48.17	48.06
8	49.09	48.95	48.81	48.67	48.54	48.42	48.29	48.17	48.06	47.94	47.83
9	48.81	48.67	48.54	48.42	48.29	48.17	48.06	47.94	47.83	47.73	47.62
10	48.54	48.41	48.29	48.17	48.06	47.94	47.83	47.73	47.62	47.52	47.42

APPENDIX B

LINK PERFORMANCE AT RECOMMENDED POWER LEVELS

This appendix contains tables and contour plots of received HP- or LP-user CNR, for user sets transmitting at recommended EIRP levels. Each LP user transmits with EIRP 23.0 dBW, and HP users transmit with EIRP 27.9 dBW. Uplink and downlink path losses are the average values of Table 2-2.

Table B-1 lists received CNR for an LP user. User sets in this table consist of one to ten LP users (including the desired user), and zero to ten HP users. Table B-2 lists received CNR for an HP user; here, user sets contain zero to ten LP users, and one to ten HP users (including the desired user). Figures B-1 and B-2 are contour plots of data from Tables B-1 and B-2, respectively.

The line drawn through the body of each table separates user sets that meet the CNR requirements of Table 3-2 from those that do not, for 4.8-kbps users in Table B-1, and for 16-kbps users in Table B-2. All user sets shown meet 2.4-kbps user CNR requirements.

TABLE B-1.
LP-User CNR (dB Hz) with Recommended EIRP

Number of HP Users	Number of LP Users										
	0	1	2	3	4	5	6	7	8	9	10
0	NA	56.55	54.48	53.59	52.78	52.14	51.58	51.09	50.65	50.25	49.89
1	NA	51.92	51.84	51.40	50.96	50.55	50.18	49.83	49.50	49.20	48.91
2	NA	51.22	50.56	50.15	49.79	49.46	49.16	48.88	48.61	48.36	48.13
3	NA	49.60	49.39	49.12	48.84	48.58	48.33	48.10	47.88	47.67	47.47
4	NA	48.80	48.54	48.30	48.07	47.85	47.64	47.44	47.25	47.07	46.89
5	NA	48.04	47.83	47.62	47.42	47.23	47.05	46.87	46.71	46.54	46.39
6	NA	47.40	47.21	47.03	46.85	46.69	46.53	46.37	46.22	46.08	45.94
7	NA	46.83	46.67	46.51	46.35	46.20	46.06	45.92	45.78	45.65	45.53
8	NA	46.34	46.19	46.04	45.90	45.77	45.64	45.51	45.39	45.27	45.15
9	NA	45.89	45.76	45.63	45.50	45.38	45.26	45.14	45.03	44.92	44.81
10	NA	45.49	45.36	45.24	45.13	45.01	44.90	44.80	44.69	44.59	44.49

TABLE B-2.
HP-User CNR (dB Hz) with Recommended EIRP

Number of HP Users	Number of LP Users										
	0	1	2	3	4	5	6	7	8	9	10
0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1	61.56	59.51	58.27	57.43	56.76	56.20	55.72	55.29	54.90	54.55	54.22
2	56.65	56.37	55.96	55.55	55.16	54.80	54.47	54.16	53.87	53.59	53.34
3	55.59	55.13	54.75	54.42	54.11	53.82	53.55	53.30	53.06	52.83	52.62
4	54.32	54.04	53.77	53.51	53.26	53.03	52.80	52.59	52.39	52.19	52.01
5	53.47	53.22	52.99	52.77	52.56	52.36	52.17	51.98	51.81	51.64	51.47
6	52.74	52.53	52.33	52.14	51.96	51.78	51.62	51.45	51.30	51.15	51.00
7	52.12	51.94	51.76	51.60	51.43	51.28	51.13	50.98	50.84	50.71	50.57
8	51.58	51.42	51.26	51.11	50.97	50.83	50.69	50.56	50.43	50.31	50.19
9	51.09	50.95	50.81	50.67	50.54	50.42	50.29	50.17	50.06	49.94	49.83
10	50.66	50.53	50.40	50.28	50.16	50.04	49.93	49.82	49.71	49.61	49.50

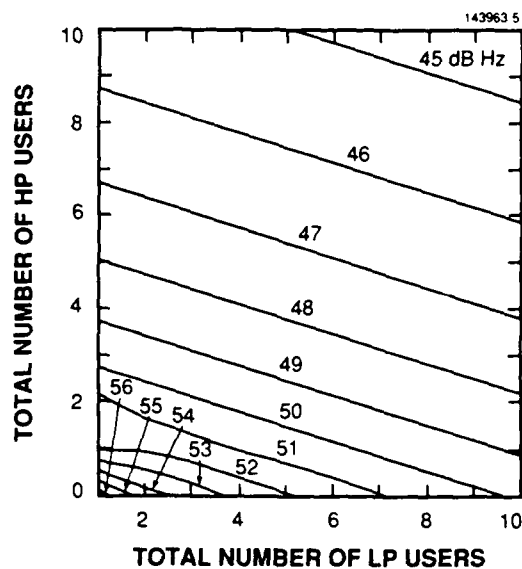


Figure B-1. CNR contours for an LP user with other LP and HP users present; LP EIRP = 23 dBW, HP EIRP = 27.9 dBW.

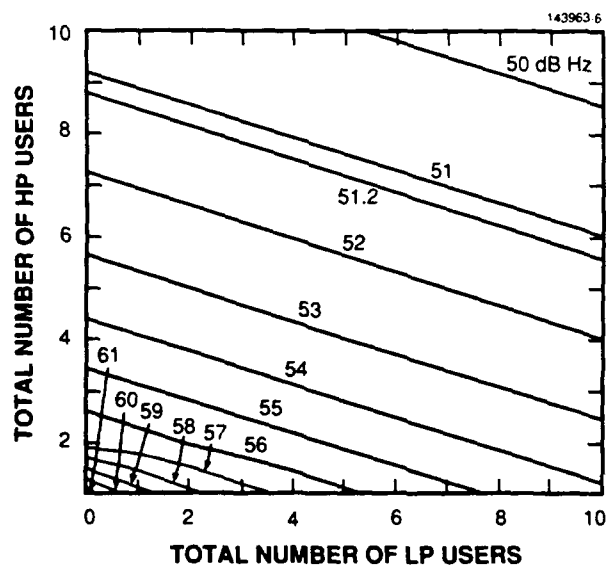


Figure B-2. CNR contours for an HP user with other LP and HP users present; LP EIRP = 23 dBW, HP EIRP = 27.9 dBW.

APPENDIX C SNR-SUPPRESSION RATIOS

This appendix describes how SNR-suppression ratios are calculated, based on the methods of References [1] and [2] for finding the time-domain description of a nonlinear device's output signal.

The transponder input signal can be written as:

$$e_i(t) = \text{Re} \left\{ \sum_{l=1}^{L+1} A_l(t) e^{j\phi_l(t)} e^{j\omega_c t} \right\} \quad (\text{C.1})$$

where:

$\text{Re}\{\cdot\}$ indicates the real part of the complex expression in braces;

ω_c is the transponder input center frequency;

$A_l(t)$ for $1 \leq l \leq L$ are (possibly time-varying) envelopes of signals 1 through L ;

$\phi_l(t)$ for $1 \leq l \leq L$ are time-varying phase offsets from $\omega_c t$, including FDM frequency offsets, and phase or frequency modulation, for signals 1 through L ;

A_{L+1} is the noise envelope, with Rayleigh distribution and variance $(2 - \pi/2)\sigma^2$;

ϕ_{L+1} is the noise phase, with uniform distribution over $(0, 2\pi)$.

For an input signal set described by Equation (C.1), the output of a nonlinear device followed by an ideal bandpass filter centered at ω_c can be written as [1,2]

$$e_o(t) = \text{Re} \left\{ e^{j\omega_c t} \sum_{k_1=-\infty}^{\infty} \cdots \sum_{k_{L+1}=-\infty}^{\infty} M(k_1, \dots, k_{L+1}, A_1, \dots, A_{L+1}) e^{j \sum_{l=1}^{L+1} k_l \phi_l(t)} \right\}. \quad (\text{C.2})$$

The particular form of the complex output envelope $M(\cdot)$ depends on the device nonlinearity, but for all cases it is true that

$$M(k_1, \dots, k_{L+1}, A_1, \dots, A_{L+1}) = 0 \quad \text{if} \quad \sum_{l=1}^{L+1} k_l \neq 1. \quad (\text{C.3})$$

This requirement reflects the bandpass nature of the nonlinearity; condition (C.3) only allows frequency components near the first harmonic of ω_c . However, there may be intermodulation products in Equation (C.3) that, while near ω_c , are outside the post-nonlinearity filter passband.

Define \underline{k}_i as the set of indices $\underline{k}_i = \{k_1, k_2, \dots, k_{L+1}\}$ such that

$$k_l = \begin{cases} 1, & l = i \\ 0, & l \neq i. \end{cases} \quad (\text{C.4})$$

Terms in the $(L + 1)$ -fold sum of Equation (C.3) can be categorized as follows:

1. Terms indexed by \underline{k}_i , for $1 \leq i \leq L$, represent signal feedthrough.
2. The term indexed by \underline{k}_{L+1} represents noise feedthrough.
3. Other nonzero terms represent intermodulation products.

If all input envelopes are constant, then signal-feedthrough terms contain no distortion. The signal envelope A_l , $1 \leq l \leq L$, of angle-modulated signals is (ideally) constant in time, but the noise envelope A_{L+1} is time-varying. Consequently, each signal-feedthrough term includes the undistorted signal with envelope $E\{M(\underline{k}_i)\}$, and signal distortion with envelope $M(\underline{k}_i) - E\{M(\underline{k}_i)\}$, where the expectations are taken over input noise.

The complex envelope $M(\cdot)$ of a given bandpass nonlinearity may be found from the single-tone output envelope $g(A)e^{jf(A)}$. The single-tone envelope is defined as the output envelope that is measured when input is a single unmodulated sinusoid of amplitude A , and noise is not present. For a bandpass hardlimiter, the single-tone output envelope is a real constant, with magnitude $g(A)e^{jf(A)} = 4C/\pi$ [9], where C is the limiter wideband output magnitude. The implied relation $f(A) = 0$ results from assuming that an ideal hardlimiter does not introduce AM/PM distortion. To evaluate $M(\cdot)$, expand the single-tone envelope as a series of first-order Bessel functions [2, Equation (3.2.2.13)] to get (after correcting a sign error in the reference)

$$g(A)e^{jf(A)} = \sum_{s=0}^{\infty} \frac{8C}{(2s+1)\pi} J_1[(2s+1)2\pi A/D] \quad (\text{C.5})$$

where D is a scale variable, as described below.

Equation (C.5) is equivalent to taking a Fourier-series expansion of the hardlimiter amplitude response and using it to compute the single-tone envelope. In order to use the Fourier-series expansion, it is necessary to assume that the hardlimiter amplitude response is periodic in input signal value, with period D . The scale factor D must be chosen so that the probability of the total input-signal-plus-noise magnitude exceeding D is very small.

Using Equation (C.5), we can write the output envelope as [2, Equation (3.2.2.14)]

$$M(k_1, \dots, k_{L+1}, A_1, \dots, A_{L+1}) = \sum_{s=0}^{\infty} \frac{8C}{(2s+1)\pi} \prod_{l=1}^{L+1} J_{k_l}[(2s+1)2\pi A_l/D]. \quad (\text{C.6})$$

This expression is separable in the deterministic input-signal and random noise components, making it a straightforward task to take the expected value with respect to input noise amplitude, and get the desired-signal (and expected-intermodulation-product) output envelopes [10, Equation 6.631 (4)]:

$$E \{M(k_1, \dots, k_{L+1}, A_1, \dots, A_{L+1})\} = \sum_{s=0}^{\infty} \frac{8C}{(2s+1)\pi} e^{-2[(2s+1)\pi\sigma/D]^2} \prod_{l=1}^L J_{k_l} [(2s+1)2\pi A_l/D]. \quad (C.7)$$

In order to find the required signal-suppression factors, Equation (C.7) is solved numerically for each k_i , $1 \leq i \leq L$.

When computing output noise power it is assumed that noise, intermodulation product, and distortion power are evenly distributed across the transponder bandwidth. Given a good method of frequency assignment, this assumption is reasonable. In the case of five 2.4-kbps channels, for example, there will be 50 third-order intermodulation-product terms, each with a spectrum three times wider than that of the input signals. If user frequencies are assigned such that no intermodulation products overlap, they will be spread over a 360-kHz-wide channel. On the other hand, if user signals are spaced a uniform distance apart across the transponder bandwidth, then most intermodulation products will fall on user signals and the assumption made here is optimistic [11].

Total transponder output power in the limiter passband is $8C^2/\pi^2$. Noise power is found by subtracting the summed signal-feedthrough power for all users from the transponder output power. Assuming uniform noise power across the transponder bandwidth, the ratio of the i^{th} signal's transponder output SNR to transponder input SNR is

$$\alpha_i = \frac{2\sigma^2}{A_i^2} \frac{E \{M(\underline{k}_i)\}^2 / 2}{\frac{8C^2}{\pi^2} - \frac{1}{2} \sum_{l=1}^L E \{M(\underline{k}_l)\}^2}. \quad (C.8)$$

This quantity is the SNR-suppression ratio for signal i . It can be written in terms of the quantities in Section 5 using

$$S_i(i) = A_n^2/2 \quad (C.9)$$

$$\sigma^2 = N_t. \quad (C.10)$$

SNR-suppression factors used in this report were found using $D = 2 \sum_{l=1}^L A_l + 6\sigma$. The series in Equation (C.7) converges rapidly. Typically, ten terms are sufficient to achieve accuracy within 0.01 percent of the final value.

One limitation that must be kept in mind when applying Equation (C.8) is that for very small output-noise power the difference in the denominator of Equation (C.8) is near zero and, consequently, the expression becomes numerically unstable. This occurs when input is strongly

dominated by one or two input signals with high SNR (> 10 dB). Such a case does not arise with present or recommended EIRP values, since the highest possible input SNR using an ARC-110 terminal is 5.1 dB.

SNR-suppression ratio results produced using the time-domain model were compared with results produced using the approach of [12] for one PM-modulated signal in noise, and the frequency-domain results of [3] for two PM-modulated signals in noise. There was good agreement for input-signal SNRs below 10 dB. With input SNR above 10 dB, output-signal powers found using time- and frequency-domain models continue to agree fairly well, but there is no longer good agreement of SNR-suppression ratios. Time-domain results in [6] show good agreement with SNR-suppression ratios from [12] for input SNR up to 20 dB, although this reference is not clear about how output-noise power was defined for the output SNR.

Figure C-1 is a contour plot of Equation (C.8) when $S_t(i)$ is equal for all signals. The two axes represent input SNR(S_t/N_t) and the number of signals present. Current input SNR values for LES-9 are -6.85 dB for LP users and -3.85 dB for HP users. By using the recommended EIRP values, input SNR would be 0.15 dB for LP users and 5.05 dB for HP users.

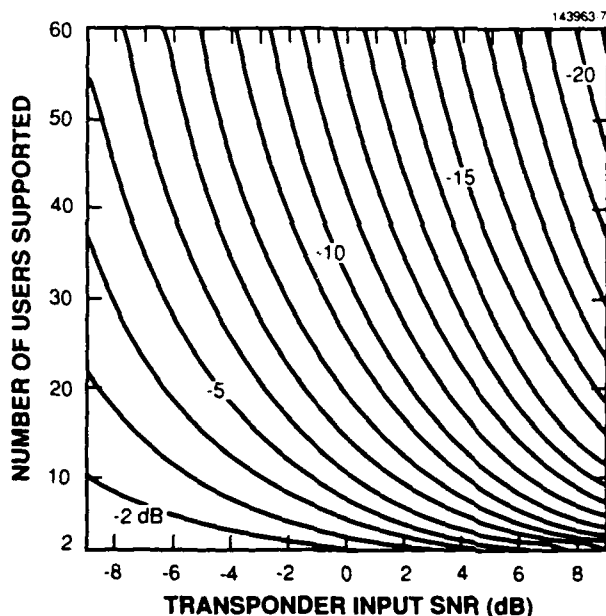


Figure C-1. SNR-suppression ratio (α) contours for equal-power users.

APPENDIX D

ACRONYMS AND ABBREVIATIONS

α_i	SNR-Suppression Ratio for i^{th} Signal
σ	Transponder Input Noise Standard Deviation
ϕ_l	l^{th} Signal (or Noise for $l = L + 1$) Frequency and Phase Offset
ω_c	Transponder Input Center Frequency
A	Single-Tone Envelope Magnitude
A_l	l^{th} Signal (or Noise for $l = L + 1$) Amplitude
ANDVT	Advanced Narrowband Digital Voice Terminal
AN/URC-110	Terminal Model
B_t	Transponder Bandwidth
BPSK	Binary Phase-Shift Keyed
C	Hardlimiter Output Magnitude (Prior to Bandlimiting)
CNR	Carrier-Power-to-Noise-Density Ratio
D	Scale Factor
dBI	Decibels Relative to Isotropically Radiated Power
dBW	Decibels Relative to 1 Watt
$e_i(t)$	Transponder Input Signal Amplitude at Time t
$e_o(t)$	Transponder Output Signal Amplitude at Time t
EIRP	Effective Isotropically Radiated Power
FDM	Frequency Division Multiplexed
FM	Frequency Modulated
FSK	Frequency-Shift Keyed
$g(A)$	Single-Tone Output Envelope Magnitude
G_r/T_{sys}	Ratio of Receive Antenna Gain to System Noise Temperature
HP	High Power
J_i	i^{th} -Order Bessel Function of the First Kind
K	Kelvins
k_i	Intermodulation Index of i^{th} Signal Output
k_l	l^{th} Component of Intermodulation Index
KY-57	Modem Model
L	Number of Users Simultaneously Supported by LES-9 Transponder
LES-9	Lincoln Experimental Satellite 9
LESOC	Lincoln Experimental Satellite Operations Center
LP	Low Power
$M(k)$	k^{th} Intermodulation-Product Envelope

NA	Not Applicable
N_d	Terminal One-Sided Noise PSD
N_r	Terminal Received Downlink Noise Power
N_t	Transponder Front-End Noise Power
P_r	Terminal Total Received Power
P_t	Transponder Received Signal Power
PM	Phase Modulated
PSD	Power Spectrum Density
$Re \{ \cdot \}$	Real Part of
RHCP	Right-Hand Circular Polarization
$S_r(i)$	Terminal Received Power Due to the i^{th} Signal
$S_t(i)$	Transponder Received Power Due to the i^{th} Signal
SNR	Signal-to-Noise Ratio
UHF	Ultra-High Frequency (225 to 400 MHz)

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